BoostMeUp: Improving Cognitive Performance in the Moment by Unobtrusively Regulating Emotions with a Smartwatch

JEAN COSTA, Cornell University, USA
FRANÇOIS GUIMBRETIÈRE, Cornell University, USA
MALTE F. JUNG, Cornell University, USA
TANZEEM CHOUDHURY, Cornell University, USA

A person's emotional state can strongly influence their ability to achieve optimal task performance. Aiming to help individuals manage their feelings, different emotion regulation technologies have been proposed. However, despite the well-known influence that emotions have on task performance, no study to date has shown if an emotion regulation technology can also enhance user's cognitive performance in the moment. In this paper, we present BoostMeUp, a smartwatch intervention designed to improve user's cognitive performance by regulating their emotions unobtrusively. Based on studies that show that people tend to associate external signals that resemble heart rates as their own, the intervention provides personalized haptic feedback simulating a different heart rate. Users can focus on their tasks and the intervention acts upon them in parallel, without requiring any additional action. The intervention was evaluated in an experiment with 72 participants, in which they had to do math tests under high pressure. Participants who were exposed to slow haptic feedback during the tests decreased their anxiety, increased their heart rate variability and performed better in the math tests, while fast haptic feedback led to the opposite effects. These results indicate that the BoostMeUp intervention can lead to positive cognitive, physiological and behavioral changes.

CCS Concepts: • **Human-centered computing → Empirical studies in ubiquitous and mobile computing**.

Additional Key Words and Phrases: cognition, cognitive, cognitive performance, cognitive enhancement, emotion regulation, self-regulation, emotion, mood, feeling, arousal, stress, anxiety, heart rate variability, HRV, heart rate, smartwatch, apple watch, wearable, mobile, haptic, feedback, feedback loop, intervention, experiment, distraction, math, mindless, unobtrusive

ACM Reference Format:
Jean Costa, François Guimbretière, Malte F. Jung, and Tanzeem Choudhury. 2019. BoostMeUp: Improving Cognitive Performance in the Moment by Unobtrusively Regulating Emotions with a Smartwatch. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 3, 2, Article 40 (June 2019), 23 pages. https://doi.org/10.1145/3328911

1 INTRODUCTION

Despite people's efforts to remain calm and collected during high-pressure situations, emotions can take control and impair their ability to have an optimal task performance. As a result, they may get a low score in the SAT or GRE, fail to deliver a speech after having "stage fright", or not succeed in a job interview due to nervousness. When felt before or during a task, high-arousal emotions such as anxiety can reduce working memory capacity [3], decrease self-confidence [31], and damage mental performance [9].

Authors' addresses: Jean Costa, Cornell University, Ithaca, NY, USA, jmd487@cornell.edu; François Guimbretière, Cornell University, Ithaca, NY, USA, francois@cs.cornell.edu; Malte F. Jung, Cornell University, Ithaca, NY, USA, mfj28@cornell.edu; Tanzeem Choudhury, Cornell University, Ithaca, NY, USA, tanzeem.choudhury@cornell.edu.

2474-9567/2019/6-ART40
https://doi.org/10.1145/3328911

When a person tries to manage their emotions during a task, it is usually because the successful execution of this task is important for her. In some cases, the goals are transient, and at other times the goals derive from enduring values associated with health, relationships, and work-related projects [36]. Aiming to achieve an optimal performance in high pressure situations, individuals use different strategies to regulate their emotions. A student might take some deep breaths during a qualifying exam, and a business person who wants to impress their work colleagues might try to suppress their nervousness during a presentation. However, decreasing high arousal emotions is not easy, and suppressing or hiding them is often ineffective [40][14].

Given the importance of emotion regulation in our lives, several technologies have been designed for this purpose [61][56][65][85]. Previous studies have shown that these technologies can help to down-regulate negative emotions, such as anxiety. Despite the usefulness of these technologies, most of them were not designed to help users regulate their emotions while focused on other activities [19]. A user can feel better by doing a deep breathing exercise presented by an app, but it is unlikely that she would be able to use this app during a high-pressure situation, such as in the middle of a job interview. Ironically, high-pressure situations are exactly the moments in which people could need more help.

Aiming to reduce user's burden in the use of emotion regulation technologies, recent research has focused on interventions that work on the periphery of user's attention. Examples include EmotionCheck, which is a watch-like device that decreases user's anxiety by providing false feedback of a slow heart rate [19]; a voice modulation intervention that makes people feel calmer by changing how they perceive the emotional tone of their own voices [20]; and a haptic intervention on the car seat that helps users do deep breathing exercises while driving [62]. In these examples, users can still perform their tasks, and the technologies act in parallel in a subtle and unobtrusive way.

Despite the evidence that emotions affect our ability to perform tasks, few studies have been conducted to evaluate how emotion regulation technologies influence user's performance. One example is the work of Paredes et al. [62], in which the authors measured if participants were able to drive properly while following breathing guidance provided by haptic or audio feedback. Verifying if the technology does not impair user's task performance is crucial to ensure that the technology does not interfere with the tasks they were designed to support [25]. However, given the numerous studies that show that people's cognitive performance is affected by their emotion regulation strategies, a technology designed to help users manage their emotions could potentially improve their cognitive performance as well.

In this paper, we present BoostMeUp, a smartwatch intervention to improve cognitive performance in the moment by regulating user's emotions unobtrusively and in parallel with their activities. To test the intervention, we conducted an experiment in which 72 participants took math tests under high pressure. Half of the participants received haptic feedback through a smartwatch representing slow heart beats, while the other half received haptic feedback representing fast heart beats. We found that the slow feedback made participants feel less anxious, have higher heart rate variability, and have better cognitive performance, while the fast feedback led to the opposite effects. The intervention did not require users to do any additional action and, more importantly, participants could focus on the math problems without attending to the smartwatch.

The main contributions of this paper can be summarized as follows:

- We present BoostMeUp, an emotion regulation intervention capable of improving user's cognitive performance in the moment;
- We show the results of a study with 72 participants in which we found that the intervention can lead to cognitive, behavioral and physiological changes;
- We present and discuss design implications of this work.

2 RELATED WORK

2.1 Interventions for Improving Cognitive Performance

Cognitive performance refers to "observable behaviour on cognitive tasks", which can include logical reasoning, memorization, decision making and problem solving [55].

Every day, people rely on several strategies for improving their cognitive performance. One common practice by millions of individuals is drinking coffee, which acts as a mild stimulant to keep people more alert and focused [13][15]. Other individuals rely on psychoactive drugs, who have been used not only to treat people with cognitive disorders but also to help individuals face stressful situations. Beta blockers, for instance, have been used by individuals with performance anxiety right before particular situations, such as musical performances and public speeches. Despite the evidence that these strategies can increase cognitive performance, there are precautions about their use in daily life. The use of psychoactive drugs, for instance, has to be prescribed by a doctor, who needs to do a thorough assessment of the patient to ensure the safe use of the medication. Even in these cases, side effects may occur. Even coffee, which is often considered safe, can have unintended health consequences if consumed excessively [15].

As an alternative to the use of stimulants and psychoactive drugs, a new trend is the use of technologies for improving cognitive performance. These technologies can also be referred as technologies for cognitive enhancement or cognitive augmentation.

Many technologies for cognitive enhancement have been designed to train people's cognitive skills [77][18]. However, although training cognitive skills is important, some researchers assert that the most likely approaches to succeed in improving cognitive performance will be those that not only directly train cognitive skills, but also indirectly support people's cognitive skills by working to reduce things that impair them and enhance things that support them [26].

One of the factors that can impair cognitive performance is distraction. Distractions attract people's attention and make them shift their focus from current tasks, which can interrupt important activities in the workplace [60] and in the classroom [37]. Because of that, several technological solutions have been proposed for helping to reduce distractions and increase user's alertness [91][45][51]. One example of technology designed to improve user's attention is AttentivU [46], which is a mobile system that measures user's attention using EEG and provides real-time feedback to nudge the person to become attentive again.

In addition to attention, memory is another cognitive process that has been targeted by designers of technologies for cognitive enhancement. Some of the first technologies designed for this purpose were wearable devices that would collect and provide relevant information to the user in real-time. One example of such technology is the Memory Glasses, which was designed to augment human memory using subliminal cueing [25]. Other technologies, such as the SenseCam [74], focus on automatically collecting data of the wearer's day, but they require users to manually look at the data collected. More recently, researchers have designed different types of interventions for memory aid [84] [47] [74][69][27], such as technologies based on augmented reality [69][27].

Another factor that affects one's cognitive performance is emotion. Cognitive processes such as decision making and problem solving are strongly affected by individual's emotional state [22]. When people are stressed, for instance, they cannot think as clearly or exercise as good self-control [26]. Because of that, individuals are constantly regulating their emotions during high-pressure situations, to ensure that their emotions will help and not harm their task performance.

2.2 Interventions for Emotion Regulation

Given the influence that emotions have in people's lives, several interventions have been designed to help individuals manage their emotions more effectively.

One target population for emotion regulation interventions are individuals with emotional disorders. Traditionally, this population has been treated with medications and/or psychotherapy treatments such as Cognitive Behavioral Therapy (CBT). More recently, it has been growing the interest in using technologies to help individuals with emotional disorders, which led to the development of technologies for people with depression [86], anxiety [58], bipolar disorder [53], and suicidal behavior [72].

In addition to helping individuals with emotional disorders, many individuals face emotional situations in which interventions could be useful. For instance, previous research has shown that the presence of stress can make any person to look like she has a cognitive disorder, such as ADHD [26]. Although individuals recognize that in some situations their stress can be debilitating, it can be hard to regulate it effectively [40][14]. For this purpose, designers and researchers proposed different types of technical interventions, including mindfulness apps such as Headspace and Calm, mobile technologies to help users manage their stress and anxiety [50][61][54][59][65][85] and virtual reality experiences to elicit positive emotions [68][2].

Despite the usefulness of existing interventions to manage emotions, users are often unable to use the available technologies during high-pressure situations, such as job interviews and public speeches, since they would need to stop their current activities to attend to the technologies [19]. Ironically, these situations are exactly the ones in which an emotion regulation technology could be more useful.

Aiming to help users manage their emotions while they are performing other activities, researchers have devised different real-time interventions. One example of this approach is the use of subtle guidance to help users change their breathing patterns. For instance, Ghandeharioun & Picard [35] presented a set of unobtrusive visual and auditory interventions to help users slow their breathing rate and feel calmer. Similarly, Paredes et al. [62] and Balters et al. [5] have proposed in-car interventions that provide guided breathing through voice or haptic feedback, either to elicit a calmer state [62] or higher arousal and alertness [5]. Another example of real-time intervention is MoodWings, which is a wearable biofeedback device that mirrors user's stress in real-time [50]. Interestingly, although the researchers expected MoodWings to calm users down, the intervention actually increased their stress level, although it also made participants to drive safer [50].

More recently, Costa et al. presented a new approach for designing emotion regulation technologies [19]. The approach consists in overriding the way users perceive emotional cues, such as their heartbeats [19] or the emotional tone of their own voices [20]. One example of such technology is EmotionCheck, which is a wearable device that can make a user believe their heart rate is much slower than it really is through slow vibrations on the wrist that resemble a pulse. A study with 67 participants has shown that this intervention can effectively reduce user's state anxiety without being distractive [19]. In another example of application of this approach, romantic couples got involved in interpersonal conflicts via Skype and some partners perceived their own voice much calmer than in reality through a real-time voice modulation software [20]. The results have shown that the partners who listened to their voices with a calmer tone felt less anxious during the conflicts.

Despite the existence of technologies for emotion regulation and for improving cognitive performance, no study to date has investigated if it is possible to improve people's cognitive performance in the moment through an emotion regulation technology. This was the aim of this research. Before developing the technology, we explored the literature of emotion, cognitive science and social psychology to understand how emotions affect cognitive performance. In the next section, we present an overview of some of the most established theories that attempt to explain the relationship between emotion, attention and performance.

2.3 Emotion, Attention and Performance

People's desire to achieve an optimal performance during tasks can lead to performance pressure [6]. Ironically, suboptimal performance is more evident when individuals want to do their best [11]. The expression "choking under pressure" has been used to describe these situations in which individuals perform more poorly than expected given their skill level [7]. According to Baumeister, there are two main groups of theories that can explain why individuals choke under pressure: drive theories and attentional theories [7].

Drive theories hold that a major determinant of a person's performance is their level of arousal, or drive [7]. The most well-known theory is called the Yerkes-Dodson Law, also called the inverted-U theory. The theory asserts that increased arousal can help improve performance, but only up to a certain point. After this point, increases in arousal lead to decreases in performance. The origin of this theory is a study from Yerkes and Dodson in which rats learned to escape from a maze more quickly when they received electric shocks at an intermediate level [90].

Building on drive theories, more recent work has attempted to explain performance failures based on interference with the attentional processes of the performer [7]. These are called attentional theories and can be separated into two types: distraction theories and explicit monitoring theories. Distraction theories assert that pressure leads to a distracting environment that compromises working memory and consequently people's performance [8]. These theories propose that performance pressure shift people's attention away from the current task to irrelevant cues. Meanwhile, explicit monitoring theories suggest that when individuals are under pressure they become more self-conscious and anxious about performing correctly [6]. This focus of attention inward prompts individuals to exert more explicit monitoring and control on the specific processes of performance.

A more recent theory that attempts to explain the relationship between anxiety and cognitive performance is attentional control theory [32]. According to the theory, anxiety affects performance by disrupting the equilibrium between two types of attention: a top-down goal-oriented attention and a bottom-up stimulus-driven attention. Top-down attention refers to the conscious focus of attention to certain features or objects, while bottom-up attention refers to salient stimuli that attract our attention even when we do not want to attend to them. The theory asserts that when a person feels anxious, there is an increase in the influence of bottom-up attention processes over top-down processes [24]. For instance, a student may try their best to focus on a test, but the feelings of anxiety may make her notice internal signals (e.g. fast heartbeat) or environmental distractions that can divert their attention away from the test. This could negatively affect the students' performance, unless she uses compensatory strategies [32].

The attentional control theory has received extensive empirical support [24]. This underscores the major role that bottom-up attention plays during anxiety-provoking situations. Some events, such as environmental noise or fast heartbeats can attract our attention pre-consciously, so we attend to them whether we want to or not [81]. This raises a question: How do peripheral emotional stimuli that we attend preconsciously affect our emotions and cognitive performance? In the next section, we present some studies that focused on answering this question.

2.4 Influence of Peripheral Emotional Stimuli on Emotions and Performance

People's reactions to peripheral emotional stimuli can help them to prepare for situations of danger or threat [63]. However, there are situations in which people's reactions harm instead of help. For example, research has shown that anxiety is associated with an attentional bias towards threatening signals and an increased distractibility in the presence of task-irrelevant cues [24]. In this way, instead of helping the person to be prepared for a challenging situation, the threatening signals can divert processing resources and negatively interfere with the person's performance [32].

One type of peripheral stimuli that can influence people's emotions are bodily signals. Studies have shown that when individuals hear sounds that resemble bodily signals, such as breathing and heart rate, individuals tend to associate these sounds with their own physiological state, which can influence their cognitive and emotional processes [64][78][79]. In a classic paper from Valins [83], for instance, male participants who listened to manipulated heart beat sounds that were allegedly their own felt more aroused and attracted to women shown on pictures. In another paper, adding naturally breath intake sounds to synthetic speech aided listeners to recall sentences [87].

Although it is well-known that emotional stimuli can affect people's emotions and performance, how to explain the fact that some people are not affected by those stimuli in some situations? According to researchers, one factor that mediates people's reactions are individual differences in sensitivity. For bodily signals, the extent of an individual's sensitivity is called interoceptive awareness [21], and it indicates how well a person is able to perceive bodily cues (e.g. heartbeats, hunger signals). Many studies have shown that there is a positive relationship between interoceptive awareness and emotional experience [67], and that the awareness of bodily signals can facilitate emotion regulation [34], intuitive decision making [28] and risk taking [43].

3 BOOSTMEUP - OVERVIEW OF THE INTERVENTION

Building on theories of emotion and cognitive performance [32][21], and previous studies that show that it is possible to reduce user's anxiety by changing their heart rate self-perception [19], we developed BoostMeUp, a smartwatch intervention designed to improve cognitive performance by regulating user's emotions in the moment.

Similar to previous technologies like EmotionCheck [19], the BoostMeUp app provides haptic feedback simulating a different heart rate. However, instead of building a physical prototype, we decided to leverage the vibration motor in a smartwatch to deliver the haptic feedback. This decision was made since millions of users already own a smartwatch [76], so an intervention designed to run in a smartwatch has a higher potential of being deployed and used in large-scale.

The BoostMeUp intervention is based on studies that show that individuals are affected by the way they perceive their own heart rate, even without their conscious awareness [83][19]. For instance, a student taking a stressful exam may notice that their heart rate is racing, and this perception can intensify feelings of anxiety [66]. The core idea of BoostMeUp is to override user's self-perception of their heart rate, by providing a different heart rate cue through haptic feedback. In this way, users are influenced to perceive the artificial heart rate feedback as their own, which can make them feel calmer when a slow feedback is provided or more aroused when a fast feedback is activated. Since the intervention relies on the way people naturally react to internal stimuli, users do not need to look at a screen or perform any additional action. Therefore, they can focus on their activities while the intervention acts upon them in parallel, without shifting their attention away.

3.1 Description of the Application

The application was developed for Apple Watch Series 3. It detects user's heart rate from the Apple Watch or from an external heart rate monitor and triggers a personalized haptic feedback using the "Taptic Engine", which provides haptic feedback using a linear resonant actuator (LRA).

The Apple Watch was chosen since it provides the most subtle haptic feedback among the smartwatches we tested. Indeed, LRAs have a lower vibration strength compared to the eccentric rotating mass vibration motors (ERM) and coin vibration motors [57], which are the most common types found in smartwatches and smartphones. The "Taptic Engine" allows developers to use 9 notification types, which provide haptic cues with different intensity and frequency levels. After a preliminary evaluation of users' experiences with different notification types used as heart beats, we found that the 'Click' type was the only type available that was noticeable without being distracting. The sensation reminds a light tapping on the wrist. Therefore, we decided to use this notification type in the application.

In order to deliver the feedback in the background, the application starts a workout session, which allows to provide haptic feedback even with the screen off. By using the workout session, we can also collect heart rate in the background. Currently, it is possible to obtain heart rate data from the Apple Watch every 5 seconds. Although this is fine to detect user's heart rate while resting or during activities, it does not provide the granularity we wanted to evaluate the effect of the intervention on users' emotions. In particular, heart rate variability (HRV) has been shown to be a reliable objective measure of mental stress [44], but it requires the collection of interbeat intervals, which refer to the time in milliseconds from one heart beat to another. However, the only way of collecting interbeat intervals with the Apple Watch at this moment is through the Breathe app, since Apple has not released methods for developers to directly access interbeat intervals or heart rate variability [38]. Because of that, we developed for the iPhone side of the application a method for the collection of interbeat intervals from heart rate monitors that use the standard Bluetooth protocol (e.g. Polar H7).

In its current implementation, the BoostMeUp app starts the haptic feedback whenever the user presses a button on an iPhone app or on the Apple Watch, or whenever a heart rate threshold is detected (e.g. above 100 bpm). In order to deliver an appropriate haptic feedback for the user, the application takes into account user's heart rate baseline to personalize the feedback. During a resting activity, the application detects user's average heart rate using the Apple Watch or an external heart rate monitor, and saves this information to later provide haptic feedback at a certain percentage below the average (to elicit lower arousal) or above the average (to elicit higher arousal). This feature was based on previous research that has shown that it is possible to make individuals underestimate or overestimate their own heart rate by providing an adjusted heart rate feedback based on individual's baseline [64].

3.2 Adjustment of Heart Rate Feedback

In order to select the appropriate percentage to adjust the heart rate feedback, we conducted a pilot study with 10 participants to evaluate people's perception of the haptic feedback with 8 frequency adjustments, using four frequency adjustments for a slower feedback (-10%, -20%, -30%, -40%), and four adjustments for a faster feedback (+10%, +20%, +30%, +40%). Participants received a personalized haptic feedback with each of the adjustments, and were asked to inform on a scale from 1 (Extremely slow) to 6 (Extremely fast) how fast was the tapping on the Apple Watch. Based on the results of this pilot, we found that 30% was the best percentage to convey the perception of a slow or fast feedback. However, some participants with very high or low heart rate baselines would still perceive the haptic feedback as fast with the feedback 30% lower than their baseline, or slow with the feedback 30% above their baseline. To avoid that, we used the same upper (65 bpm) and lower (40 bpm) frequency limits used in previous research for the slow feedback [4], and to keep the same heart rate range for the frequency limits (25 bpm) we used 80 bpm and 105 bpm as lower and upper frequency limits for the fast feedback. The lower limit of 80 bpm was selected since it was the threshold in which all participants started to perceive the feedback as fast.

4 STUDY: EFFECT OF BOOSTMEUP DURING MATH TESTS

Many individuals have test anxiety, which refers to symptoms of anxiety felt before or during test-taking situations [71]. These symptoms can strongly disturb people's learning and performance [70]. There are two separate dimensions of test anxiety: cognitive and affective. The cognitive dimension, also called "worry", refers to concerns about performance and a potential failure, and the affective dimension, also referred as "emotionality", corresponds to the awareness of physiological reactions, such as increased heart rate and sweating [49][88].

Since the awareness of physiological reactions is a core dimension of test anxiety, an intervention that changes people's perception of their own emotionality may help individuals to manage their emotional state and improve their test performance. Therefore, we decided to evaluate the effect of the BoostMeUp intervention during stressful test-taking situations.

We conducted a laboratory experiment in which participants had to take two math tests under pressure. All participants were exposed to the haptic feedback intervention during one math test and another math test was used as control (no feedback was provided). Half of the participants received haptic feedback representing a slow heart rate, while the other half received a fast feedback. We collected cognitive, physiological and behavioral measures from participants to investigate if the intervention would affect all dimensions consistently.

A double-blind protocol was adopted to prevent participant response bias and experimenter bias. The double-blind protocol was ensured by using the BoostMeUp application to pick a condition randomly from a counterbalanced set, without the awareness of the researcher or the participants.

The application and the tests used in this study are available upon request. You can contact us through this link: http://pac.cs.cornell.edu/boostmeup/.

5 HYPOTHESES

Previous studies have shown that people's perception of their own bodily signals can influence their emotional experience [83][66]. By providing heart rate feedback, either through sounds [83][79] or haptic cues [19][4], it is possible to elicit an emotional state congruent with the feedback frequency. A slow feedback elicits lower arousal and a calmer state [19][4], while a fast feedback elicits higher arousal [83][29]. In addition to the subjective perception of stress and anxiety, individuals tend to have particular physiological reactions when under stress, such as low heart rate variability. This leads to our first hypothesis:

> ***Hypothesis 1 (H1)****: The slow haptic feedback will decrease the anxiety and increase the heart rate variability of the participants, while the fast haptic feedback will increase their anxiety and decrease their heart rate variability*

According to Attentional Control Theory, anxiety impairs cognitive performance by disrupting people's attentional control [32]. Therefore, by reducing a person's anxiety during a stressful task, this should lead to an improvement in cognitive performance, while increasing their anxiety should lead to performance declines. This leads to our second hypothesis:

> ***Hypothesis 2 (H2)****: The slow haptic feedback will increase the performance of the participants, while the fast haptic feedback will decrease their performance*

6 METHOD

6.1 Setup

The study was conducted in a sound-treated room in an academic department. The room contained a small table and two chairs. The room was set up with one laptop on the table, which was used by the participants to perform all tasks of the study. Next to the laptop we left the following mobile devices: i) Apple Watch Series 3 ii) Heart rate monitor (Polar H7). Both devices were used by all participants during the experiment. The Apple Watch had the BoostMeUp app installed to deliver the haptic feedback, while the heart rate monitor was used to extract the heart rate variability measures.

6.2 Task

We used modular arithmetic for our math task. The object of modular arithmetic is to judge if problem statements such as $51 \equiv 19 \pmod 4$ are true or false [10]. This problem can be solved by subtracting the middle number from the first number (51-19) and then dividing the difference by the last number (32/4). If the dividend is a whole number, the answer is "true". Modular arithmetic is a good choice for this study since it is novel and challenging, even to individuals highly experienced in math [10]. All modular arithmetic problems used in this study had a carry operation during the subtraction step and could not be solved by simple heuristics. This was done to ensure that all questions had high working memory demands [52].

6.3 Experimental Conditions

All participants had to take two math tests, one was used for the control condition, in which no haptic feedback was triggered on the Apple Watch, and the other was used for the haptic feedback condition. The conditions were counterbalanced across participants to avoid order effects. Participants were assigned to one of two groups: slow or fast. Depending on the assigned group, participants received a particular type of haptic feedback.

For the **slow condition**, the Apple Watch triggered a constant tapping at a frequency 30% slower (mean=57.10, s.d.=13.19) than the participant's baseline heart rate (mean=78.72, s.d.=12.25), as collected during a relaxation phase. However, lower (40 bpm) and upper (65 bpm) frequency limits were imposed to prevent vibrations to be perceived as unnaturally slow or fast, respectively.

For the **fast condition**, the Apple Watch triggered a constant tapping at a frequency 30% faster (mean=97.25, s.d.=8.92) than the participant's baseline heart rate (mean=76.54, s.d.=10.50) . However, lower (80 bpm) and upper (105 bpm) frequency limits were imposed to prevent vibrations to be perceived as slow or too fast, respectively.

6.4 Procedure

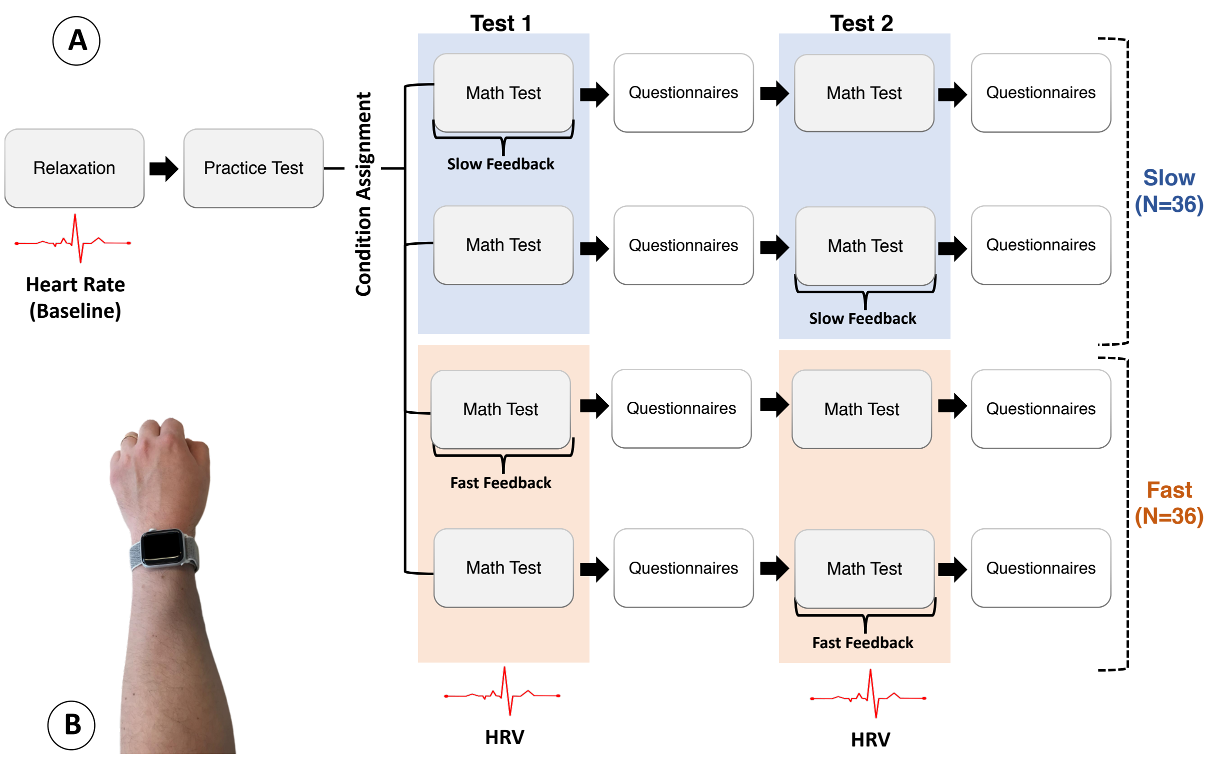

Fig. 1. The study design (A) and the position of the Apple Watch used during the study (B)

A graphical illustration of the study's design can be seen in Fig. 1. Before the experiment, all participants completed a consent form in which they were introduced to the study. Participants were informed that the focus of the study was on investigating students' emotions and performance during exams.

After signing the consent form, participants received instructions to place the heart rate monitor and the Apple Watch in a private room. They were instructed to put the smartwatch in their non-dominant wrist and in a firm but comfortable position. One researcher verified if the Apple Watch was correctly placed and if the data from all devices could be properly collected. Next, the researcher informed: "We will collect your heart rate during certain moments of the experiment. While we are collecting your heart rate with the smartwatch, you might feel a subtle tapping on your wrist that could be based on your heart rate or not". By providing this information, we could evaluate the effectiveness of the intervention without providing false information about the feedback, which was the approach used in previous research [19]. If the intervention works even in this context, it means that the use of false feedback is not necessary.

After these instructions, participants were informed that they would perform all tasks of the experiment with the computer in front of them. No additional material was given for the participants.

In the relaxation phase of the experiment, participants watched a calming video for 5 minutes. This phase was used to make participants relax and collect their baseline heart rate. The baseline heart rate was used to personalize the haptic feedback used in a later phase of the experiment.

After the relaxation phase, participants were asked to complete a series of questions about their demographics, math anxiety, state and trait anxiety [75]. Once the questionnaires were completed, participants read the instructions for the math test:

> ”You will complete IQ tests with 36 questions under time pressure. Each question has the following format: $51 \equiv 19 \pmod 4$. To answer this question, you will need to calculate 51 minus 19, divided by 4. For each problem, if the solution is a whole number (like here, 8), then then correct answer is "true". If the solution is not a whole number, then the correct answer is "false". Please find below some examples of other problems with the corresponding solutions. After understanding how to solve the problems, please click on the button "PRACTICE TEST" to start the practice test.”

The instructions included 3 examples of math problems in which the solution was true and 3 examples in which the solution was false. After participants read the instructions, they started the practice test. We did not collect data during the practice test. The inclusion of the practice test served two purposes: i) help participants familiarize with the test format; ii) reduce the likelihood of a much higher arousal and anxiety in the first math test used in the experiment.

After the practice test, the researcher started the condition with the BoostMeUp app. Participants could be assigned to one of the following conditions: 1) slow feedback group; feedback in first test; 2) slow feedback group; feedback in second test; 3) fast feedback group; feedback in first test; 4) fast feedback group; feedback in second test. Figure 1 shows the 4 possible paths. The haptic feedback was counterbalanced for both groups (slow and fast) to mitigate order effects caused by the delivery of the feedback in the first or second test. The tests for which the haptic feedback was not activated were used as control.

Once the participant was assigned to one condition, she started the math test phase. This phase included a waiting period of 2 minutes and 3 minutes for the actual math test. The waiting period was included to elicit pre-performance anxiety and also to help participants get used to the haptic feedback in case it was active. During the waiting period, participants read the following instructions on the computer screen:

> ”Please wait for the beginning of the test. The test will start automatically in 2 minutes.
> For each question, you will have five seconds to select the correct answer. If you answer all test questions correctly, you will earn \$2.50 per test (\$5 total). For each question you answer incorrectly or do not answer, you will lose 10 cents (\$0.10). Good luck minimizing your loss”.

These instructions were used to make participants feel more anxious, since pressure, loss framing, the expectation of monetary rewards, and the phrase "IQ test" tend to make people very anxious [10][9][23][14].

During the test, participants had to press one of two buttons ("True" or "False") to answer each math problem. Each problem remained on the screen for 5 seconds. After 5 seconds, a new math problem would appear. If participants did not press a button on time, it would count as one missed question.

After finishing the test, participants were automatically redirected to a new set of questionnaires. Next, participants were redirected to the last math test. Once participants finished the last math test, they answered the same set of questionnaires and additional questions about their experience during the tests.

After completing the tasks and questionnaires, a semi-structured interview was conducted. The purpose of this interview was to obtain information about participants' perception of their emotions, performance, and the tapping felt during the study. Then, participants were debriefed, thanked, and paid for their participation.

6.5 Measures

6.5.1 Cognitive Anxiety. We used the State-Trait Anxiety Inventory (STAI) [75] to measure participants' cognitive anxiety. The STAI consists of 40 self-report items focused on anxiety affect. 20 items are used to assess state anxiety, and another 20 items to assess trait anxiety. State anxiety corresponds to the transitory emotion, while trait anxiety is the individual's predisposition to respond to anxiety-provoking situations [30][75]. The state anxiety questionnaire contains items such as "I am worried; I feel calm", while the trait anxiety questionnaire contains items such as "I worry too much over something that really doesn't matter". After the person finishes a questionnaire, an anxiety score that ranges from 20 to 80 can be obtained. In this study, since the goal was to evaluate the effect of the intervention on transient emotions, we used only the state anxiety questionnaire after each math test.

6.5.2 Physiological Responses. In order to measure people's physiological responses to the tasks, we used a heart rate monitor (Polar H7) to collect heart rate variability (HRV) measures. HRV refers to the variation in the interval between consecutive heart beats (called RR intervals) and consecutive instantaneous heart rates [16]. This variation is under the control of the Autonomous Nervous System (ANS), which is responsible for adjusting the HRV in response to physical or emotional stimuli [17]. A normal and healthy person shows a good degree of variation of the heart rate, reflecting a good capability to react to those stimuli [16], but during stressful situations the autonomous nervous system is disturbed, which results in a decreased HRV (lower parasympathetic activity) [39].

In this study, we collected time-domain and frequency-domain HRV measures that allow to measure the parasympathetic function of the ANS.

Time-domain HRV measures can be used to quantify the amount of variability in the interval between successive heart beats. Among the measures, some of the most commonly used are RMSSD, NN50 and pNN50. We used these three measures in our analysis.

Frequency-domain measures estimate the distribution of power (absolute or relative) into four frequency bands: ultra-low-frequency (ULF), very-low-frequency (VLF), low-frequency (LF), and high-frequency (HF) [16][73]. There is a general consensus that HF power declines during emotionally stressful tasks [33][73]. Therefore, we decided to use the HF measure in our analysis.

Table 1 shows the HRV measures collected in our study with the corresponding descriptions. All measures were obtained using the software Kubios HRV [80]. For all these measures, higher values indicate lower mental stress.

6.5.3 Performance. In order to measure people's cognitive performance, we used three measures of performance in the test: 1) percentage of correct questions; 2) number of missed questions; and 3) average time in milliseconds to answer each question.

Table 1. Selected measures of heart rate variability (HRV)

Variable	Unit	Description
Time-Domain Measures		
RMSSD	ms	Root mean square of successive RR interval differences
NN50	Count	Number of adjacent RR intervals that differ from each other by more than 50 ms
pNN50	%	Percentage of successive RR intervals that differ by more than 50 ms
Frequency-Domain Measures		
HF	ms^2	Absolute power of the high-frequency band (0.15 - 0.4 Hz)

6.6 Participants

72 subjects participated in the study (50 Female; mean age=20.2, s.d.=1.5). Participants ranged from 18 to 25 years of age. All participants were students at a large US university. Students were recruited via an on-campus web-based recruitment system and received $10 cash as a show-up fee and up to $5 as additional compensation based on their performance in the tests.

7 RESULTS

We conducted a two-way between-subjects analysis of variance using the rate (slow, fast) and the order (feedback in first test, feedback in second test) as independent variables. For all measures used in this study, we computed the difference between the measure obtained for the test in which the feedback was applied, and the measure obtained for the control test (no feedback). These differences were used as dependent variables in our analysis.

In order to ensure that violations in the normality assumption would not influence the analysis, we used the Aligned Rank Transform (ART) [89] for nonparametric data. ART enables nonparametric factorial data analysis by "aligning" data before applying averaged ranks, which allows the use of ANOVA afterwards [89].

We did not find significant differences between the two groups (slow feedback and fast feedback) at baseline and during the control test that could confound our results. At baseline, we did not find significant differences in gender (p=.31), age (p=.24), education (p=.61), math anxiety (p=.26), and heart rate (p=.41). Similarly, during the math test used as control, we did not find significant differences between the two groups for state anxiety (p=.60), for the HRV measures RMSSD (p=.99), NN50 (p=.71), pNN50 (p=.89), and HF (p=.75), and for the performance measures accuracy (p=.57), misses (p=.56), and time (p=.10).

In the next sub-sections, we present the results showing the effect of the intervention on state anxiety, heart rate variability and performance.

7.1 State Anxiety

A two-way between-subjects ANOVA was performed to compare the main effects of rate (slow, fast) and order (feedback in first test; feedback in second test) and the interaction effect between rate and order on the state anxiety of participants. The results are shown on Table 2. The main effect of order on state anxiety was not significant (p=0.09). However, as hypothesized, there was a main effect of rate on state anxiety, $F(1, 68) = 5.18$, $p < .05$, $\eta_p^2 = .07$. As shown in Figure 2, participants felt less anxious when the slow feedback was applied ($Mean\ \Delta$ = -0.91; $SE\ \Delta$ = 0.98) and more anxious when the fast feedback was applied ($Mean\ \Delta$ = 2.36; $SE\ \Delta$ = 1.23). There was no significant interaction between rate and order (p=0.31).

7.2 Heart Rate Variability (HRV)

Separate two-way between-subjects ANOVAs were carried out for each dependent measure of heart rate variability. The results are shown on Table 3. As we predicted, there was a main effect of rate on the time-domain measures

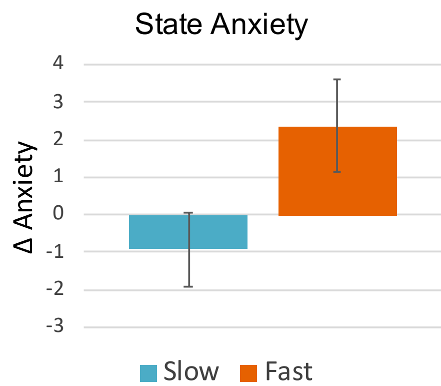

Fig. 2. Bar plot showing the anxiety changes (anxiety after feedback - anxiety after control) for the slow and fast feedback conditions

Table 2. ANOVA results for state anxiety

		df	F	η_p^2	p
	Rate	**1,68**	**5.18***	**.07**	**.02**
ANXIETY	Order	1,68	2.81	.03	.09
	Rate*Order	1,68	1.04	.01	.31

RMSSD (p<.05), NN50 (p<.01), pNN50 (p<.01), and on the frequency-domain measure HF (p<.05). There was also a main effect of order on the measure HF (p<.01), but not on the other measures. There were no significant interactions between rate and order for any of the dependent variables. As shown in Figure 3, the changes in the HRV measures happened as predicted. When participants received the slow haptic feedback, there were increases in the HRV measures RMSSD (*Mean* Δ = 4.94; *SE* Δ = 2.66), NN50 (*Mean* Δ = 7.33; *SE* Δ = 2.87), pNN50 (*Mean* Δ = 1.98; *SE* Δ = 0.84), and HF (*Mean* Δ = 114.09; *SE* Δ = 62.56). On the other hand, for participants who received the fast haptic feedback, there were decreases in the HRV measures RMSSD (*Mean* Δ = -2.50; *SE* Δ = 1.59), NN50 (*Mean* Δ = -5.83; *SE* Δ = 3.35), pNN50 (*Mean* Δ = -1.67; *SE* Δ = 1.04), and HF (*Mean* Δ = -118.97; *SE* Δ = 59.80).

7.3 Performance

Separate two-way between-subjects ANOVAs were carried out using each performance measure as a dependent variable. All results can be found in Table 4. As we hypothesized, there were main effects of rate on the performance measures accuracy (p<.05), missed questions (p<.05), and average time (p<.001). There were no main effects of order and no significant interactions between order and rate. Participants who received the slow feedback answered more questions correctly (*Mean* Δ = 4.86%; *SE* Δ = 2.08), with 1.75 more correct questions, while participants who received the fast feedback had a decline in performance (*Mean* Δ = -1.6%; *SE* Δ = 1.91), with 0.58 less correct questions. Participants also missed less questions while receiving the slow feedback (*Mean* Δ = -1.25; *SE* Δ = 0.58), and missed more questions when receiving the fast feedback (*Mean* Δ = 0.72; *SE* Δ = 0.56). One result that we did not anticipate was the effect of the intervention on the time to answer the questions. Different from what we predicted, participants answered the questions slower when the slow feedback was active (*Mean* Δ

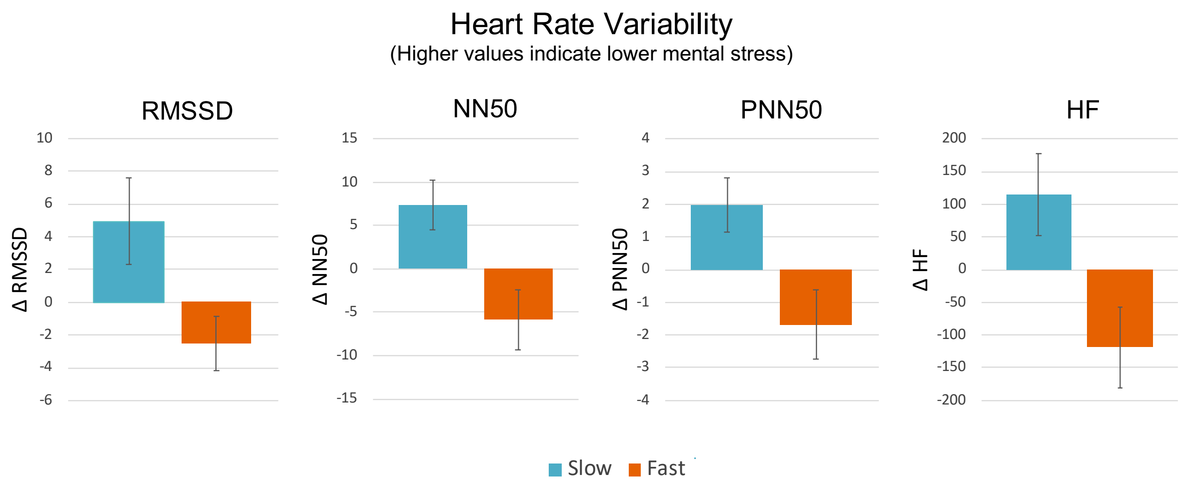

Fig. 3. Bar plots showing all HRV changes (feedback measure - control measure) for the slow and fast feedback conditions

Table 3. ANOVA results for each HRV measure

		df	F	η_p^2	p
	Rate	**1,68**	**6.66***	**.08**	**.01**
RMSSD	Order	1,68	2.96	.04	.08
	Rate*Order	1,68	0.03	.0005	.85
	Rate	**1,68**	**10.99****	**.13**	**.001**
NN50	Order	1,68	1.26	.01	.26
	Rate*Order	1,68	0.45	.006	.50
	Rate	**1,68**	**10.57****	**.13**	**.001**
pNN50	Order	1,68	2.29	.03	.13
	Rate*Order	1,68	0.48	.007	.48
	Rate	**1,68**	**5.16***	**.07**	**.02**
HF	**Order**	**1,68**	**8.47****	**.11**	**.004**
	Rate*Order	1,68	0.11	.001	.73

= 261.14 ms; *SE* Δ = 52.07), while participants answered the questions faster when the fast feedback was active (*Mean* Δ = -130.9 ms; *SE* Δ = 91.29). All these changes in performance for each feedback group can be seen in Figure 4.

7.4 Distraction

During the study, participants were asked to report how distracting was the tapping on the smartwatch on a scale from 1 (Not at all) to 5 (A great deal). The answers to this question are summarized in Figure 5. To have a better

Fig. 4. Bar plots showing all performance changes (feedback measure - control measure) for the slow and fast feedback conditions

Table 4. ANOVA results for each performance measure

		df	F	η_p^2	p
ACCURACY	**Rate**	**1,68**	**5.15****	**.07**	**.02**
	Order	1,68	0.57	.008	.45
	Rate*Order	1,68	0.49	.007	.48
MISSES	**Rate**	**1,68**	**6.29***	**.08**	**.01**
	Order	1,68	0.23	.003	.63
	Rate*Order	1,68	1.59	.02	.21
TIME	**Rate**	**1,68**	**13.87*****	**.16**	**.0003**
	Order	1,68	0.94	.01	.33
	Rate*Order	1,68	0.87	.01	.35

understanding about participants' experiences, the same question was asked in the end during a semi-structured interview.

In the slow feedback condition, 25 participants (69.4%) thought that the tapping was not distracting at all. Participants said that they could notice the tapping, but it did not shift their attention away during the test ("*I was aware of it but I was too focused on the test to really think about it*", P23). Five participants (13.8%) thought that the tapping was a little distracting. They mentioned that they could notice the tapping, but none of them expressed that it affected their performance ("*The tapping was very slightly distracting, but not to the point that it affected my performance or my concentration*", P55). Two participants (5.5%) expressed that the tapping was moderately distracting. One of these participants mentioned that she gets distracted easily, and pointed to the soundproof foam on the wall to explain that ("*I get distracted very easily, like these walls are distracting me*", P46). Finally, 4 participants (11.1%) said that the tapping distracted them a lot. Interestingly, one of these participants

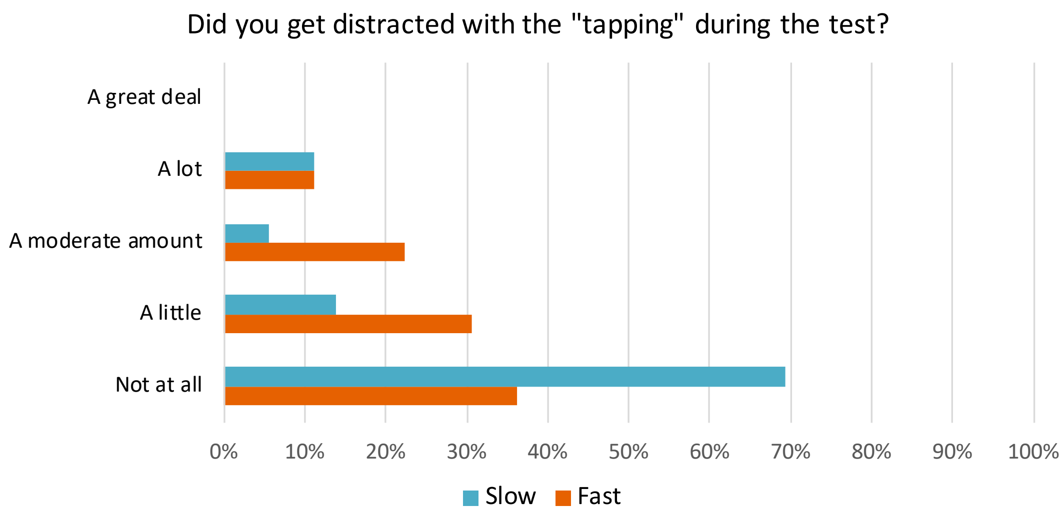

Fig. 5. Summary of the results for the question about how distracting was the haptic feedback

thought that the tapping was speeding up, although the frequency was constant during the study ("*I thought the clicking on the watch was pretty distracting. It felt like it was speeding up over the course of the test and it made me think that the clicking was my heart rate*", P10). This participant also mentioned that the feedback was mostly distracting in the beginning of the test ("*I think it was really weird for the first half of the test but then I kind of got used to it and then it faded into the background.*", P10).

In the fast feedback condition, 13 participants (36.1%) expressed that the feedback was not distracting at all ("*I definitely noticed the tapping but I don't think it was a distraction by any means*", P69). 11 participants (30.5%) mentioned that the feedback distracted them slightly. Similar to the answers given to the slow feedback, these participants also did not think it affected their performance ("*I was mainly trying to focus on the questions, I don't think anything else popped into my head*", P25). 8 participants (22.2%) considered the feedback moderately distracting, and expressed that it likely affected their performance in the tests ("*I didn't notice the tapping at first. I noticed it middle way and I got distracted. There were a few questions that I didn't answer because I was just focusing on the tapping*", P65). Finally, 4 participants (11.1%) said that the tapping distracted them a lot. These participants also mentioned that they thought their performance was worse because of the tapping ("*I probably did pretty badly on both tests, but the second one maybe slightly worse because I would think of the tapping here and there and it would distract me momentarily*", P17). Overall, more participants thought that the fast feedback was distracting in comparison to the slow feedback.

8 DISCUSSION

In the present research, we evaluated the effect of the BoostMeUp intervention on state anxiety, heart rate variability and cognitive performance during stressful math tests. All the results of the study support our hypotheses, showing that the BoostMeUp intervention can lead to positive cognitive, physiological and behavioral changes. It is important to note that these changes were seen with an intervention that lasted only 5 minutes, and did not require users to do any additional action or attend to the technology. This means that this intervention has the potential of being easily used as needed throughout the day, without requiring user's conscious attention or effort [1].

8.1 Effect of the Intervention on Anxiety and HRV

The first hypothesis of this study was that the slow feedback would make participants feel less anxious and have higher HRV, while the fast feedback would make participants feel more anxious and have lower HRV. The results of the study support this hypothesis. However, the effect of the slow feedback on state anxiety was smaller than what has been reported in previous studies that used a similar approach [19][4]. Two things could potentially explain the smaller effect size found in our study. First, the design of the studies is different. In [4], for instance, the experimental task elicited pre-performance anxiety, so participants were exposed to the feedback in anticipation of a stressful task, rather than in the middle of a stressful task. Second, while in previous studies participants received deceptive information about the purpose and the feedback provided by the interventions [19][4], in our study we did not provide false feedback. Instead, participants were informed that the tapping felt on their wrist through the smartwatch could represent their heart rate or not. Previous studies have demonstrated that people's emotional self-judgments are influenced by the feedback provided by emotion tracking technologies [42], so it is possible that the use of false feedback boosts the cognitive effect of the intervention on anxiety.

Consistent with the effect of the intervention on state anxiety, the intervention also influenced participants' heart rate variability. As we hypothesized, participants had higher HRV when they received the slow feedback and lower HRV when they received the fast feedback. Previous research has shown that HRV can be used as a objective measure of mental stress [44][73]. Therefore, the results provide evidence that the slow feedback intervention made participants feel calmer, while the fast feedback intervention made participants feel more stressed. This is the first study to show that a wearable technology that provides haptic feedback that resembles heartbeats can influence user's heart rate variability.

8.2 Effect of the Intervention on Performance

Finally, the second hypothesis of this study was that participants would have a higher performance when receiving the slow feedback, and lower performance when receiving the fast feedback. As we predicted, participants that received the slow feedback answered more questions correctly and missed less questions, while participants that received the fast feedback committed more mistakes and missed more questions. These results show that the BoostMeUp intervention influenced participants' cognitive performance.

The effect of the intervention on the time to answer the questions was the opposite of what we expected. Participants answered the questions slower when they received the slow feedback and answered them faster when they received the fast feedback. We will discuss two potential explanations for this effect.

First, while solving problems under time constraints, individuals have to make a choice between optimizing for accuracy or optimizing for speed, which is called the speed-accuracy tradeoff [12]. Studies indicate that the anxiety felt while solving mathematical problems can lead people to sacrifice accuracy while confronted with difficult problems, either to avoid having to deal with the problem or to speed up the task [3]. When individuals are experiencing high levels of anxiety, they may have a tendency to answer questions faster, while less anxious subjects can allow themselves more time to consider their answers, which leads to higher accuracy but slower response time [48]. Therefore, it is possible that the increase in anxiety caused by the fast feedback led participants to try to optimize for speed, which made them rush to answer the questions. On the other hand, participants who received the slow feedback may have tried to optimize for accuracy, which led them to take their time to answer the questions properly.

The second potential explanation for the effect of the intervention on time is that the haptic feedback frequency had an effect on people's perception of time, which influenced their behavior during the math tests. Interestingly, some participants mentioned during the interview that they thought that the time to answer the questions was longer when the slow feedback was active, while other participants mentioned that the fast feedback made them perceive the time as faster. For example, one participant from the fast feedback group mentioned about the second test (in which the haptic feedback was active): *"I think the second test was slightly faster because it felt like I had slightly less time to answer the questions"*. Similarly, another participant from the slow feedback group mentioned: *"The questions were changing at a slower rate"*.

In order to understand why the intervention caused an effect on the average time to answer questions, we will conduct future studies to investigate the aforementioned hypotheses.

8.3 Unobtrusiveness of the Intervention

In addition to influencing participants' anxiety, HRV and cognitive performance, our results show that the slow feedback was considered unobtrusive by most participants. Participants mentioned that they could notice the feedback, but they were able to focus on the tests without shifting their attention away. The fact that, on average, participants who received the slow feedback improved their performance and had lower physiological arousal, corroborates the evidence that the intervention was not distracting. The fast feedback, on the other hand, was considered distracting by many participants, which was expected since the goal of the fast feedback was to increase user's state anxiety.

Although the slow feedback was not distracting at all for the majority of participants, some participants mentioned that the intervention compromised their attention during the test. It is possible that the novelty effect and the fact that participants knew the tapping was going to happen primed some participants to pay attention to the haptic feedback. In order to evaluate if that is the case, a study could be conducted to evaluate if participants habituate to the feedback over time. Some participants in the slow feedback group also mentioned that they perceived the feedback as fast, which means that the feedback adjustment did not work as intended for some participants. To mitigate this issue, the application could allow the user to manually calibrate the haptic feedback, so that the user could select a more appropriate option based on their own perception. Finally, it is also possible that the intervention might not be suitable for everyone, especially for individuals who get distracted very easily. In these cases, adding another signal for people to notice, even a subtle one, could be more harmful than helpful.

9 IMPLICATIONS FOR DESIGN

9.1 Emotion Regulation as a Medium for Behavior Change

A significant amount of studies that evaluate emotion regulation technologies focus on the emotional changes caused by their use. This is expected, since these technologies are designed to regulate emotions anyway. However, one question that needs to be asked is: Why do people use technologies to regulate how they feel? In many cases, users want to feel better and the emotional outcome is their end goal. However, there are several circumstances in which individuals use emotion regulation strategies as a medium to achieve a behavioral outcome [41]. People recognize that their feelings and the corresponding physiological signals play a major role in their task performance, and they try to manage their emotional state to ensure that their emotions will be helpful rather than harmful. Therefore, we argue that in addition to investigating how technologies help users manage their feelings, it is important to evaluate how these technologies impact user's activities. One way of accomplishing that is by using performance measures to evaluate if the interventions disturb people's activities. Previous studies have used this approach [50][35][62], and have shown that it is possible to intervene in real-time without impairing people's ongoing tasks. However, no study so far had shown that emotion regulation technologies can also improve user's cognitive performance in the moment. In this paper, we show for the first time an intervention that can cause not only cognitive and physiological effects, but also positive behavioral outcomes in cognitive tasks. Participants who received a slow haptic feedback through a smartwatch felt calmer, answered more questions correctly and missed less questions in math tests.

9.2 False Feedback is Not Necessary

In this study, we found that it is possible to lower user's anxiety and even improve their cognitive performance without providing false information about the feedback provided by the technology. Previous research has shown that mobile health apps can lead to digital placebo effects, in which the beliefs and expectations of the users can directly influence the outcomes of the interventions [82]. Similarly, previous studies have shown that individuals' beliefs about the feedback presented by emotion tracking technologies can affect their own emotional self-judgments [19][42]. The results of these studies highlight one crucial aspect of technological interventions: what users are informed about the technologies and their purpose matters. In Costa et. al [19], for instance, the authors provided false feedback simulating a slow heart rate and found that this led participants to feel less anxious. The use of deception and cover stories in lab experiments is common to avoid participant response bias. However, in real-world situations it would be unethical not to inform participants about the feedback inaccuracy. In order to avoid this issue, in this research we informed participants that the heart rate feedback provided by the smartwatch could be accurate or not. In this way, we could evaluate if our approach works even when users do not know if the feedback is indeed truthful. The results of the study show that false feedback is not necessary for the intervention to be effective, which brings this intervention one step closer to be used in the wild.

10 LIMITATIONS AND FUTURE WORK

Despite the positive results of this study, we acknowledge some limitations that could be addressed in future research. The first limitation is that all participants were young college students, ranging from 18 to 25 years to age. Therefore, we cannot generalize our findings to a broader population. However, since many college students experience mental stress and anxiety during academic tasks, the intervention offers promising opportunities to help college students during stressful activities, such as exams.

Another limitation of this study is that the tasks were conducted in a laboratory environment, so it is still uncertain if the intervention would be effective in the wild. In real world situations, individuals would be exposed to more external stimuli, so it is unclear if the perception of a slow or fast haptic feedback can still have a significant effect when there are more signals competing for attention. We are currently planning a longitudinal study to evaluate if the BoostMeUp intervention can also lead to positive outcomes in-situ. This study will also enable us to investigate the long-term effects of the intervention.

Finally, in this study participants had to solve challenging modular arithmetic problems that require high working memory demands. Although the intervention was effective in this context, more research is needed to evaluate the effectiveness of BoostMeUp in other scenarios. For example, the theories that explain how anxiety affects performance during mental tests [32] are not the same used to explain "choking under pressure" in sports [6]. In a future study, we plan to investigate if the intervention is also effective during high-pressure situations that require perceptual-motor skills.

11 CONCLUSIONS

We presented BoostMeUp, a smartwatch intervention capable of improving user's cognitive performance in the moment by regulating their emotions unobtrusively and in parallel with their activities. The intervention was inspired by theories that explain the relationship between emotions and cognitive performance [7][32], and previous studies that show that it is possible to influence people's emotions by changing how they perceive their own heart rate [19]. Based on these theories and studies, we developed a smartwatch application that leverages the vibration motor of a smartwatch to deliver personalized haptic feedback that resembles heartbeats. To evaluate the intervention, we conducted an experiment with 72 participants in which they answered math problems under pressure. Each participant took two math tests, in which one test was used as control and the other test was used to deliver either a slow or fast haptic feedback. Participants who received the slow feedback felt less anxious, had higher heart rate variability and performed better in the math tests, while participants who received the fast feedback felt more anxious, had lower heart rate variability and performed worse. These consistent results using cognitive, physiological and behavioral measures provide strong evidence that the intervention is effective. Furthermore, participants did not have to do any additional action or shift their attention away from the math tests, which shows that the intervention can act on the periphery of people's attention. These findings open space for a new generation of emotion regulation technologies that not only help people to improve their feelings, but also boost their task performance.

ACKNOWLEDGMENTS

This material is based upon work supported by the NSF FW-HTF #1840167 and by Microsoft.

REFERENCES

[1] Alexander T Adams, Jean Costa, Malte F Jung, and Tanzeem Choudhury. 2015. Mindless computing: designing technologies to subtly influence behavior. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 719–730.

[2] Judith Amores, Xavier Benavides, and Pattie Maes. 2016. Psychicvr: Increasing mindfulness by using virtual reality and brain computer interfaces. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 2–2.

[3] Mark H Ashcraft and Elizabeth P Kirk. 2001. The relationships among working memory, math anxiety, and performance. *Journal of experimental psychology: General* 130, 2 (2001), 224.

[4] Ruben Azevedo, Nell Bennett, Andreas Bilicki, Jack Hooper, Fotini Markopoulou, and Manos Tsakiris. 2017. The calming effect of a new wearable device during the anticipation of public speech. *Scientific reports* 7, 1 (2017), 2285.

[5] Stephanie Balters, Elizabeth L Murnane, James A Landay, and Pablo E Paredes. 2018. Breath Booster!: Exploring In-Car, Fast-Paced Breathing Interventions to Enhance Driver Arousal State. In *Proceedings of the 12th EAI International Conference on Pervasive Computing Technologies for Healthcare*. ACM, 128–137.

[6] Roy F Baumeister. 1984. Choking under pressure: self-consciousness and paradoxical effects of incentives on skillful performance. *Journal of personality and social psychology* 46, 3 (1984), 610.

[7] Roy F Baumeister and Carolin J Showers. 1986. A review of paradoxical performance effects: Choking under pressure in sports and mental tests. *European Journal of Social Psychology* 16, 4 (1986), 361–383.

[8] Roy F Baumeister and Kathleen D Vohs. 2007. *Encyclopedia of social psychology*. Vol. 1. Sage.

[9] Sian L Beilock. 2008. Math performance in stressful situations. *Current Directions in Psychological Science* 17, 5 (2008), 339–343.

[10] Sian L Beilock and Thomas H Carr. 2005. When high-powered people fail: Working memory and "choking under pressure" in math. *Psychological science* 16, 2 (2005), 101–105.

[11] Sian L Beilock, Catherine A Kulp, Lauren E Holt, and Thomas H Carr. 2004. More on the fragility of performance: choking under pressure in mathematical problem solving. *Journal of Experimental Psychology: General* 133, 4 (2004), 584.

[12] Rafal Bogacz, Eric-Jan Wagenmakers, Birte U Forstmann, and Sander Nieuwenhuis. 2010. The neural basis of the speed–accuracy tradeoff. *Trends in neurosciences* 33, 1 (2010), 10–16.

[13] Carolyn F Brice and Andrew P Smith. 2002. Effects of caffeine on mood and performance: a study of realistic consumption. *Psychopharmacology* 164, 2 (2002), 188–192.

[14] Alison Wood Brooks. 2014. Get excited: Reappraising pre-performance anxiety as excitement. *Journal of Experimental Psychology: General* 143, 3 (2014), 1144.

[15] Masood Sadiq Butt and M Tauseef Sultan. 2011. Coffee and its consumption: benefits and risks. *Critical reviews in food science and nutrition* 51, 4 (2011), 363–373.

[16] AJMM Camm, Marek Malik, JTGB Bigger, Günter Breithardt, Sergio Cerutti, R Cohen, Philippe Coumel, E Fallen, H Kennedy, RE Kleiger, et al. 1996. Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *Circulation* 93, 5 (1996), 1043–1065.

[17] Rossana Castaldo, Paolo Melillo, Umberto Bracale, M Caserta, Maria Triassi, and Leandro Pecchia. 2015. Acute mental stress assessment via short term HRV analysis in healthy adults: A systematic review with meta-analysis. *Biomedical Signal Processing and Control* 18 (2015), 370–377.

[18] Baek-Hwan Cho, Jeonghun Ku, Dong Pyo Jang, Saebyul Kim, Yong Hee Lee, In Young Kim, Jang Han Lee, and Sun I Kim. 2002. The effect of virtual reality cognitive training for attention enhancement. *CyberPsychology & Behavior* 5, 2 (2002), 129–137.

[19] Jean Costa, Alexander T Adams, Malte F Jung, François Guimbretière, and Tanzeem Choudhury. 2016. EmotionCheck: leveraging bodily signals and false feedback to regulate our emotions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 758–769.

[20] Jean Costa, Malte F Jung, Mary Czerwinski, François Guimbretière, Trinh Le, and Tanzeem Choudhury. 2018. Regulating Feelings During Interpersonal Conflicts by Changing Voice Self-perception. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 631.

[21] Hugo D Critchley, Stefan Wiens, Pia Rotshtein, Arne Öhman, and Raymond J Dolan. 2004. Neural systems supporting interoceptive awareness. *Nature neuroscience* 7, 2 (2004), 189.

[22] Antonio R Damasio. 1994. Descartes' error: Emotion, rationality and the human brain. (1994).

[23] Marci S DeCaro, Robin D Thomas, Neil B Albert, and Sian L Beilock. 2011. Choking under pressure: Multiple routes to skill failure. *Journal of Experimental Psychology: General* 140, 3 (2011), 390.

[24] Nazanin Derakshan and Michael W Eysenck. 2009. Anxiety, processing efficiency, and cognitive performance: New developments from attentional control theory. *European Psychologist* 14, 2 (2009), 168–176.

[25] Richard W DeVaul, Vicka R Corey, et al. 2003. The memory glasses: subliminal vs. overt memory support with imperfect information. In *null*. IEEE, 146.

[26] Adele Diamond and Daphne S Ling. 2016. Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental cognitive neuroscience* 18 (2016), 34–48.

[27] Stefania Druga, Pattie Maes, and Alexandra Rieger. 2017. Motif: a wearable sonic cueing device for memory support and cognitive intervention. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. ACM, 180–185.

[28] Barnaby D Dunn, Hannah C Galton, Ruth Morgan, Davy Evans, Clare Oliver, Marcel Meyer, Rhodri Cusack, Andrew D Lawrence, and Tim Dalgleish. 2010. Listening to your heart: How interoception shapes emotion experience and intuitive decision making. *Psychological science* 21, 12 (2010), 1835–1844.

[29] Anke Ehlers, Jürgen Margraf, Walton T Roth, C Barr Taylor, and Niels Birbaumer. 1988. Anxiety induced by false heart rate feedback in patients with panic disorder. *Behaviour research and therapy* 26, 1 (1988), 1–11.

[30] Norman S Endler and Nancy L Kocovski. 2001. State and trait anxiety revisited. *Journal of anxiety disorders* 15, 3 (2001), 231–245.

[31] Michael W Eysenck and Manuel G Calvo. 1992. Anxiety and performance: The processing efficiency theory. *Cognition & Emotion* 6, 6 (1992), 409–434.

[32] Michael W Eysenck, Nazanin Derakshan, Rita Santos, and Manuel G Calvo. 2007. Anxiety and cognitive performance: attentional control theory. *Emotion* 7, 2 (2007), 336.

[33] Mark Fenton-O'Creevy, Jeffrey T Lins, Shalini Vohra, Daniel W Richards, Gareth Davies, and Kristina Schaaff. 2012. Emotion regulation and trader expertise: Heart rate variability on the trading floor. *Journal of Neuroscience, Psychology, and Economics* 5, 4 (2012), 227.

[34] Jürgen Füstös, Klaus Gramann, Beate M Herbert, and Olga Pollatos. 2012. On the embodiment of emotion regulation: interoceptive awareness facilitates reappraisal. *Social cognitive and affective neuroscience* 8, 8 (2012), 911–917.

[35] Asma Ghandeharioun and Rosalind Picard. 2017. BrightBeat: Effortlessly Influencing Breathing for Cultivating Calmness and Focus. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 1624–1631.

[36] James J Gross. 2002. Emotion regulation: Affective, cognitive, and social consequences. *Psychophysiology* 39, 3 (2002), 281–291.

[37] Caroline A Guardino and Elizabeth Fullerton. 2010. Changing behaviors by changing the classroom environment. *Teaching Exceptional Children* 42, 6 (2010), 8–13.

[38] David Hernando, Surya Roca, Jorge Sancho, Álvaro Alesanco, and Raquel Bailón. 2018. Validation of the apple watch for heart rate variability measurements during relax and mental stress in healthy subjects. *Sensors* 18, 8 (2018), 2619.

[39] Nis Hjortskov, Dag Rissén, Anne Katrine Blangsted, Nils Fallentin, Ulf Lundberg, and Karen Søgaard. 2004. The effect of mental stress on heart rate variability and blood pressure during computer work. *European journal of applied physiology* 92, 1-2 (2004), 84–89.

[40] Stefan G Hofmann, Sanna Heering, Alice T Sawyer, and Anu Asnaani. 2009. How to handle anxiety: The effects of reappraisal, acceptance, and suppression strategies on anxious arousal. *Behaviour research and therapy* 47, 5 (2009), 389–394.

[41] Victoria Hollis, Artie Konrad, and Steve Whittaker. 2015. Change of heart: emotion tracking to promote behavior change. In *Proceedings of the 33rd annual ACM conference on human factors in computing systems*. ACM, 2643–2652.

[42] Victoria Hollis, Alon Pekurovsky, Eunika Wu, and Steve Whittaker. 2018. On Being Told How We Feel: How Algorithmic Sensor Feedback Influences Emotion Perception. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 3 (2018), 114.

[43] Narayanan Kandasamy, Sarah N Garfinkel, Lionel Page, Ben Hardy, Hugo D Critchley, Mark Gurnell, and John M Coates. 2016. Interoceptive ability predicts survival on a London trading floor. *Scientific reports* 6 (2016), 32986.

[44] Hye-Geum Kim, Eun-Jin Cheon, Dai-Seg Bai, Young Hwan Lee, and Bon-Hoon Koo. 2018. Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature. *Psychiatry investigation* 15, 3 (2018), 235.

[45] Young-Ho Kim, Jae Ho Jeon, Eun Kyoung Choe, Bongshin Lee, KwonHyun Kim, and Jinwook Seo. 2016. TimeAware: Leveraging framing effects to enhance personal productivity. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM,

272–283.

[46] Nataliya Kosmyna, Utkarsh Sarawgi, and Pattie Maes. 2018. AttentivU: Evaluating the Feasibility of Biofeedback Glasses to Monitor and Improve Attention. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. ACM, 999–1005.

[47] Stacey Kuznetsov, Anind K Dey, and Scott E Hudson. 2009. The effectiveness of haptic cues as an assistive technology for human memory. In *International Conference on Pervasive Computing*. Springer, 168–175.

[48] Marjorie R Leon and William Revelle. 1985. Effects of anxiety on analogical reasoning: A test of three theoretical models. *Journal of Personality and Social Psychology* 49, 5 (1985), 1302.

[49] Robert M Liebert and Larry W Morris. 1967. Cognitive and emotional components of test anxiety: A distinction and some initial data. *Psychological reports* 20, 3 (1967), 975–978.

[50] Diana MacLean, Asta Roseway, and Mary Czerwinski. 2013. MoodWings: a wearable biofeedback device for real-time stress intervention. In *Proceedings of the 6th international conference on PErvasive Technologies Related to Assistive Environments*. ACM, 66.

[51] Gloria Mark, Shamsi Iqbal, and Mary Czerwinski. 2017. How blocking distractions affects workplace focus and productivity. In *Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers*. ACM, 928–934.

[52] Andrew Mattarella-Micke, Jill Mateo, Megan N Kozak, Katherine Foster, and Sian L Beilock. 2011. Choke or thrive? The relation between salivary cortisol and math performance depends on individual differences in working memory and math-anxiety. *Emotion* 11, 4 (2011), 1000.

[53] Mark Matthews, Saeed Abdullah, Elizabeth Murnane, Stephen Voida, Tanzeem Choudhury, Geri Gay, and Ellen Frank. 2016. Development and evaluation of a smartphone-based measure of social rhythms for bipolar disorder. *Assessment* 23, 4 (2016), 472–483.

[54] Mark Matthews, Jaime Snyder, Lindsay Reynolds, Jacqueline T Chien, Adam Shih, Jonathan W Lee, and Geri Gay. 2015. Real-time representation versus response elicitation in biosensor data. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 605–608.

[55] Richard E Mayer. 2003. What causes individual differences in cognitive performance. *The psychology of abilities, competencies, and expertise* (2003), 263–273.

[56] Daniel McDuff, Amy Karlson, Ashish Kapoor, Asta Roseway, and Mary Czerwinski. 2012. AffectAura: an intelligent system for emotional memory. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 849–858.

[57] Pardis Miri, Robert Flory, Andero Uusberg, Helen Uusberg, James J Gross, and Katherine Isbister. 2017. HapLand: A Scalable Robust Emotion Regulation Haptic System Testbed. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 1916–1923.

[58] David C Mohr, Kathryn Noth Tomasino, Emily G Lattie, Hannah L Palac, Mary J Kwasny, Kenneth Weingardt, Chris J Karr, Susan M Kaiser, Rebecca C Rossom, Leland R Bardsley, et al. 2017. IntelliCare: an eclectic, skills-based app suite for the treatment of depression and anxiety. *Journal of medical Internet research* 19, 1 (2017).

[59] Neema Moraveji, Ben Olson, Truc Nguyen, Mahmoud Saadat, Yaser Khalighi, Roy Pea, and Jeffrey Heer. 2011. Peripheral paced respiration: influencing user physiology during information work. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*. ACM, 423–428.

[60] Brid O'Conaill and David Frohlich. 1995. Timespace in the workplace: Dealing with interruptions. In *Conference companion on Human factors in computing systems*. ACM, 262–263.

[61] Pablo Paredes and Matthew Chan. 2011. CalmMeNow: exploratory research and design of stress mitigating mobile interventions. In *CHI'11 Extended Abstracts on Human Factors in Computing Systems*. ACM, 1699–1704.

[62] Pablo E Paredes, Yijun Zhou, Nur Al-Huda Hamdan, Stephanie Balters, Elizabeth Murnane, Wendy Ju, and James A Landay. 2018. Just Breathe: In-Car Interventions for Guided Slow Breathing. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1 (2018), 28.

[63] Elizabeth A Phelps, Sam Ling, and Marisa Carrasco. 2006. Emotion facilitates perception and potentiates the perceptual benefits of attention. *Psychological science* 17, 4 (2006), 292–299.

[64] Geoffrey C Phillips, Gary E Jones, Eric J Rieger, and Jeffry B Snell. 1999. Effects of the presentation of false heart-rate feedback on the performance of two common heartbeat-detection tasks. *Psychophysiology* 36, 4 (1999), 504–510.

[65] Inmaculada Plaza, Marcelo Marcos Piva Demarzo, Paola Herrera-Mercadal, and Javier García-Campayo. 2013. Mindfulness-based mobile applications: literature review and analysis of current features. *JMIR mHealth and uHealth* 1, 2 (2013).

[66] Olga Pollatos, Beate M Herbert, Ellen Matthias, and Rainer Schandry. 2007. Heart rate response after emotional picture presentation is modulated by interoceptive awareness. *International Journal of Psychophysiology* 63, 1 (2007), 117–124.

[67] Olga Pollatos, Wladimir Kirsch, and Rainer Schandry. 2005. On the relationship between interoceptive awareness, emotional experience, and brain processes. *Cognitive Brain Research* 25, 3 (2005), 948–962.

[68] Giuseppe Riva, Fabrizia Mantovani, Claret Samantha Capideville, Alessandra Preziosa, Francesca Morganti, Daniela Villani, Andrea Gaggioli, Cristina Botella, and Mariano Alcañiz. 2007. Affective interactions using virtual reality: the link between presence and

emotions. *CyberPsychology & Behavior* 10, 1 (2007), 45–56.

[69] Oscar Rosello, Marc Exposito, and Pattie Maes. 2016. NeverMind: using augmented reality for memorization. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 215–216.

[70] Spencer J Salend. 2012. Teaching students not to sweat the test. *Phi Delta Kappan* 93, 6 (2012), 20–25.

[71] Kristin D Sawka-Miller. 2011. Test Anxiety. In *Encyclopedia of Child Behavior and Development*. Springer, 1478–1479.

[72] Jessica Schroeder, Chelsey Wilkes, Kael Rowan, Arturo Toledo, Ann Paradiso, Mary Czerwinski, Gloria Mark, and Marsha M Linehan. 2018. Pocket Skills: A Conversational Mobile Web App To Support Dialectical Behavioral Therapy. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 398.

[73] Fred Shaffer and JP Ginsberg. 2017. An overview of heart rate variability metrics and norms. *Frontiers in public health* 5 (2017), 258.

[74] Ana R Silva, Salomé Pinho, Luís M Macedo, and Chris J Moulin. 2013. Benefits of SenseCam review on neuropsychological test performance. *American journal of preventive medicine* 44, 3 (2013), 302–307.

[75] Charles D Spielberger. 2010. State-Trait anxiety inventory. *The Corsini encyclopedia of psychology* (2010), 1–1.

[76] Nick Statt. 2018. Apple Watch remains best-selling wearable with 4.7 million shipments last quarter. https://www.theverge.com/2018/9/4/17820290/apple-watch-sales-idc-report-best-selling-smartwatch-wearable-market Accessed: 2019-02-01.

[77] Joshua R Steinerman. 2010. Minding the aging brain: technology-enabled cognitive training for healthy elders. *Current Neurology and neuroscience reports* 10, 5 (2010), 374–380.

[78] Ana Tajadura-Jiménez, Aleksander Väljamäe, Frédéric Bevilacqua, and Nadia Bianchi-Berthouze. 2017. Body-Centered Auditory Feedback. *The Wiley Handbook of Human Computer Interaction Set* (2017), 371.

[79] Ana Tajadura-Jiménez, Aleksander Väljamäe, and Daniel Västfjäll. 2008. Self-representation in mediated environments: the experience of emotions modulated by auditory-vibrotactile heartbeat. *CyberPsychology & Behavior* 11, 1 (2008), 33–38.

[80] Mika P Tarvainen, Juha-Pekka Niskanen, Jukka A Lipponen, Perttu O Ranta-Aho, and Pasi A Karjalainen. 2014. Kubios HRV–heart rate variability analysis software. *Computer methods and programs in biomedicine* 113, 1 (2014), 210–220.

[81] Jan Theeuwes. 1991. Exogenous and endogenous control of attention: The effect of visual onsets and offsets. *Perception & psychophysics* 49, 1 (1991), 83–90.

[82] John Torous and Joseph Firth. 2016. The digital placebo effect: mobile mental health meets clinical psychiatry. *The Lancet Psychiatry* 3, 2 (2016), 100–102.

[83] Stuart Valins. 1966. Cognitive effects of false heart-rate feedback. *Journal of personality and social psychology* 4, 4 (1966), 400.

[84] Sunil Vemuri and Walter Bender. 2004. Next-generation personal memory aids. *BT Technology Journal* 22, 4 (2004), 125–138.

[85] Jay Vidyarthi and Bernhard E Riecke. 2014. Interactively mediating experiences of mindfulness meditation. *International Journal of Human-Computer Studies* 72, 8-9 (2014), 674–688.

[86] Sarah Watts, Anna Mackenzie, Cherian Thomas, Al Griskaitis, Louise Mewton, Alishia Williams, and Gavin Andrews. 2013. CBT for depression: a pilot RCT comparing mobile phone vs. computer. *BMC psychiatry* 13, 1 (2013), 49.

[87] Doug H Whalen, Charles E Hoequist, and Sonya M Sheffert. 1995. The effects of breath sounds on the perception of synthetic speech. *The Journal of the Acoustical Society of America* 97, 5 (1995), 3147–3153.

[88] Allan Wigfield and Judith L Meece. 1988. Math anxiety in elementary and secondary school students. *Journal of educational Psychology* 80, 2 (1988), 210.

[89] Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM, 143–146.

[90] Robert M Yerkes and John D Dodson. 1908. The relation of strength of stimulus to rapidity of habit-formation. *Journal of comparative neurology and psychology* 18, 5 (1908), 459–482.

[91] Chuang-Wen You, Nicholas D Lane, Fanglin Chen, Rui Wang, Zhenyu Chen, Thomas J Bao, Martha Montes-de Oca, Yuting Cheng, Mu Lin, Lorenzo Torresani, et al. 2013. Carsafe app: Alerting drowsy and distracted drivers using dual cameras on smartphones. In *Proceeding of the 11th annual international conference on Mobile systems, applications, and services*. ACM, 13–26.

Received February 2019; revised April 2019; accepted April 2019